THE CORRELATION FUNCTION OF FLUX-LIMITED X-RAY CLUSTERS

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ABSTRACT

We show that the spatial correlation function of a flux-limited sample of X-ray selected clusters of galaxies will exhibit a correlation scale that is smaller than the correlation scale of a volume-limited, richness-limited sample of comparable apparent spatial density. The flux-limited sample contains clusters of different richnesses at different distances: poor groups are found nearby and rich clusters at greater distances. Since the cluster correlation strength is known to increase with richness, the flux-limited sample averages over the correlations of poor and rich clusters. On the other hand, a volume-limited, richness-limited sample has a minimum richness threshold, and a constant mixture of richnesses with redshift. Using the observed correlation scale for rich ($R \geq 1$) clusters, $r_o(R \geq 1) = 21 \pm 2h^{-1}$Mpc that was determined from previous volume-limited studies, we derive for the ROSAT flux-limited X-ray cluster sample $r_o(\text{flux}-\text{limited}) \approx 14h^{-1}$Mpc, in agreement with the recently observed value of $13.7 \pm 2.3h^{-1}$Mpc.

Cosmology: large-scale structure of Universe – galaxies: clusters of – X-rays: galaxies

1. INTRODUCTION

The correlation function of clusters of galaxies constrains cosmological models for the formation and evolution of structure in the universe (White et al. 1987; Bahcall 1988; Suginohara & Suto 1991; Bahcall & Cen 1992; Croft & Efstathiou 1993). The cluster correlation function is known to be stronger than the correlation function of galaxies; the correlation scale of the rich and rare clusters of richness class $R \geq 1$ is $r_o(R \geq 1) = 21 \pm 2h^{-1}$Mpc (Bahcall & Soneria 1983; Postman et al. 1992; Peacock & West 1992), while the galaxy correlation scale is $r_o(g) = 5h^{-1}Mpc$ (Groth & Peebles 1977). The cluster correlation strength is observed to increase with cluster richness: rich, rare clusters exhibit stronger correlations than the more numerous poor clusters and groups (Bahcall & Soneira 1983; Bahcall & West 1992). All samples of clusters studied so far, from poor groups of galaxies to the richest $R \geq 1$ and $R \geq 2$ Abell clusters, including the intermediate richness clusters observed by the new automated cluster surveys of the EDCC (Nichol et al. 1992) and APM (Dalton et al. 1992) are consistent with a universal richness-dependent correlation (Bahcall & West 1992). Large-scale cosmological N-body simulations of galaxy clusters also show the same dependence of the cluster correlation function on richness (Bahcall & Cen 1992; Croft & Efstathiou 1993). This richness-dependent correlation function applies to complete richness-limited samples of clusters (i.e., clusters above a given richness threshold); it represents the underlying spatial distribution of a system of clusters of a given richness class.

Recently, the spatial correlation function of a sample of X-ray clusters of galaxies detected in a flux-limited survey of the ROSAT X-ray satellite was reported (Romer et al. 1993). The sample contains all X-ray sources above a given

X-ray flux threshold that are associated with a local galaxy density enhancement. A correlation length of $r_o = 13.7 \pm 2.3h^{-1}$Mpc was determined for the sample. Romer et al.(1993) conclude, from a direct comparison of this correlation length and the larger length of the rich $R \geq 1$ clusters, that inconsistencies exist between the two results, and that the $R \geq 1$ cluster correlation scale has been overestimated.

In the present letter we show that a *flux-limited* sample, such as the X-ray sample described above, differs significantly from a richness-limited sample (such as the $R \geq 1$ clusters from which the $21h^{-1}$Mpc scale length was obtained). The flux-limited sample is a "richness-mixed" sample; it contains, by definition, poor clusters nearby and rich clusters at greater distances. Since cluster correlations depend on richness, a simple comparison between the correlation properties of a flux-limited and a richness-limited sample is inappropriate. Here we show that, based on the richness-dependent correlation function and a correlation scale of $r_o(R \geq 1) = 21 \pm 2h^{-1}$Mpc for $R \geq 1$ clusters, the expected correlation scale for the above flux-limited X-ray sample is $r_o(\mathrm{flux-limited}) \approx 2/3 r_o(R \geq 1) = 14h^{-1}$Mpc, as is indeed observed. This first X-ray selected ROSAT cluster sample thus confirms the richness-dependent cluster correlation function.

2. THE CORRELATION FUNCTION OF A FLUX-LIMITED X-RAY SAMPLE

The richness-dependent cluster correlation function is represented by (Bahcall & Soneira 1983; Bahcall & West 1992)

$$\xi_{cc}(r) \approx 4Nr^{-1.8} \quad , \tag{1}$$

where $\xi_{cc} = Ar^{-1.8} = (r/r_o)^{-1.8}$ is the standard form of the correlation function

(with an amplitude A and a correlation scale r_o), and N is the *median* richness of the cluster sample. Relation (1) applies to complete volume-limited, richness-limited samples (all clusters above a threshold richness limit); it represents the spatial distribution of clusters of a given richness class. Similarly, the cluster correlation amplitude also depends on the mean separation of clusters, d (where $d = n^{-1/3}$, and n is the space-density of the cluster sample). This led to the universal dimensionless cluster correlation function (Szalay & Schramm 1985; Bahcall & West 1992)

$$\xi_{cc}(d) = 0.2(r/d)^{-1.8} = (r/0.4d)^{-1.8} \ , \quad \text{i.e.,} \qquad r_o \approx 0.4d \qquad . \tag{2}$$

The above-described universal correlation function is seen both in observations and in model simulations (Bahcall & Cen 1992). It applies to complete volume-limited, richness-limited samples, where n and d represent the underlying density and mean separation of a *complete* system of clusters above a given richness threshold. All the principal cluster samples analyzed to-date for which relations (1) and (2) apply are volume and richness limited (e.g., Abell, Zwicky, APM, EDCC clusters, and groups; see summary in Bahcall & West 1992).

Recently, a flux-limited correlation function of X-ray clusters was determined by Romer et al. (1993). The sample includes all X-ray sources above a flux threshold of $F_x \geq 10^{-12}$ergs cm^{-2} s^{-1}. A total of 161 sources associated with some enhancement in the galaxy density distribution are detected in a 3100 deg^2 region; 128 of these systems have measured redshifts. Romer et al. find $r_o = 13.7 \pm 2.3 h^{-1}$Mpc for the correlation function of this flux-limited redshift sample (for a correlation slope of -1.9 ± 0.4). They contrast this correlation scale with the value of $r_o = 21 \pm 2 h^{-1}$Mpc observed for the rich $R \geq 1$ clusters.

However, the volume-limited and the flux-limited samples are not expected to yield the same correlation scales, since the criteria for inclusion in the two samples are different. The volume-limited sample includes all clusters above a given richness threshold; the flux-limited sample includes a mixture of richnesses that is a function of redshift. The *average* observed cluster density, n, and mean separation, d, of the flux-limited sample are *not* representative of a given richness system, and thus can not be applied in relations (1) and (2).

What would the correlation function of such a flux-limited sample be if the underlying cluster correlation is represented by the richness-dependent universal correlation function (relations 1 and 2)? We address this question below.

An observational relation exists, as expected theoretically, between the X-ray luminosity of clusters and cluster temperature, or mass. Henry & Arnaud (1991) find that, for a Hubble constant of $H_o = 100h$km s^{-1} Mpc^{-1} (where $h = 1$ will be used throughout), $L_x(\mathrm{Bol}) = 2.5 \times 10^{42} T^{2.7\pm0.4}$, where $L_x(\mathrm{Bol})$ is the bolometric X-ray luminosity of the cluster in erg s^{-1}, and T is the intracluster gas temperature in keV. Edge & Stewart (1991) find similar results, with $L_x(\mathrm{Bol}) = 2.5 \times 10^{42} T^{2.5}$ (see also Henry et al. 1992 and David *et al.* 1993 for similar relations). Converting the bolometric luminosity to the ROSAT observed energy band of 0.1-2.4 keV (for the typical range of cluster temperatures $T \sim 2 - 10$ keV), we find $L_x(0.1 - 2.4\mathrm{keV}) \approx 2.8 \times 10^{42} T^{2\pm0.4}$ergs s^{-1}. The virial mass of a cluster is proportional to the temperature, T, or to the square of peculiar velocity in the cluster, σ: $M \propto T \propto \sigma^2$ (Sarazin 1988; Bahcall & Cen 1993; Lubin & Bahcall 1993). Lubin and Bahcall find, on average, $\sigma = 400T^{0.5}$ km s^{-1} for the best $\sigma \propto T^{0.5}$ observed relation. The virial cluster mass within $1.5h^{-1}$Mpc of the cluster center, assuming an isothermal density profile, is then

$M(< 1.5h^{-1}\mathrm{Mpc}) = 2\sigma^2 R(1.5)/G \approx 1.1 \times 10^{14} T(\mathrm{keV})$. Combining the above relations we find

$$L_x(0.1 - 2.4\mathrm{keV}) \approx 2.2 \times 10^{42} (M/10^{14} M_\odot)^{2\pm 0.4} \mathrm{ergs\ s^{-1}} \quad . \tag{3}$$

The above relation is consistent with the theoretically expected dependence resulting from the thermal bremsstrahlung origin of the X-ray emission: $L_x(\mathrm{Bol}) \propto M_{gas}^2 T^{0.5} \propto M^{2.5}$ (for an approximately constant size of the X-ray emitting region, and $M_{gas} \propto M$). This yields $L_x(0.1 - 2.4) \propto M^2$, consistent with eq. (3).

Using eq. (3) above, the observed X-ray flux of a cluster is

$$F_x(0.1 - 2.4\mathrm{keV}) \approx 2.2 \times 10^{42} (M/10^{14} M_\odot)^{2\pm 0.4} / 4\pi d^2 \mathrm{ergs\ cm^{-2}\ s^{-1}} \quad , \tag{4}$$

where d is the luminosity-distance of the cluster. The flux is therefore proportional, approximately, to $F \propto (M/d)^2$. For a flux-limited sample, the nearby clusters have a low mass (and thus a low richness) threshold, and the distant clusters have a richer threshold. In a flux-limited sample the number density of clusters decreases faster for poor clusters than for rich clusters. A volume-limited sample, on the other hand, has a cluster density that remains constant (in comoving coordinates) for each richness class.

To calculate the expected correlation function of a flux-limited X-ray cluster sample, we use N-body simulations that match the correlation function of the observed richness threshold cluster samples ($R \geq 1$ clusters, EDCC clusters, and APM clusters). We use a large-scale Particle-Mesh code with a box size of $400h^{-1}$Mpc to simulate the evolution of the dark matter. The box contains 500^3 cells and $250^3 = 10^{7.2}$ dark matter particles. The spatial resolution is

$0.8h^{-1}$Mpc. Details of the simulations are discussed in Cen (1992) and Bahcall & Cen (1992). A model that reproduces the observed mass-function of clusters, as well as the observed correlation function of the richness-threshold $R \geq 1$, APM, and EDCC clusters is a low-density, unbiased CDM model (Bahcall & Cen 1992). This model, with $\Omega = 0.2$, $h = 0.5$, and no bias ($b = 1$) produces the observed richness-dependent universal cluster correlation function (eq. 1-2), and is consistent with other cluster properties such as their mass-function.

Clusters are selected in the simulation box using an adaptive linkage algorithm following the procedure described in Suto, Cen & Ostriker (1992) and Bahcall & Cen (1992); the cluster mass within $1.5h^{-1}$Mpc is determined. In order to extend the volume-limited sample of the underlying cluster distribution to distances of the most distant X-ray clusters observed ($z \leq 0.25$), a mosaic of eight $400h^{-1}$Mpc simulation boxes are used, corresponding to $800h^{-1}$ Mpc on a side. Within this larger mosaic box, ~ 3000 $R \geq 1$ clusters are identified in the simulation (with $n = 6 \times 10^{-6}\ h^3$Mpc^{-3}).

Each cluster of mass M (within $1.5h^{-1}$Mpc) is assigned an X-ray luminosity as given by relation (3), and an X-ray flux—to an observer at the corner of the box—as given by (4). The flux threshold of the Romer et al. (1993) sample is then applied. All clusters in the $800h^{-1}$Mpc simulation box with X-ray flux above this threshold are identified; they correspond to a flux-limited X-ray sample similar to the one observed.

The redshift distribution of the X-ray clusters in both the observed and the simulated flux-limited samples are presented in Figure 1. Two simulated cases are shown: one corresponds to relation (4) (with a 15% lower amplitude in the $F_x - M^2$ relation in order to match the observed *average* co-moving density of

X-ray clusters in the range $cz = 5000$ to 50000 km s^{-1}, $n \sim 5 \times 10^{-6} h^3 \mathrm{Mpc}^{-3}$); the other corresponds to a somewhat shallower slope than given in relation (4), $F_x \propto M^{1.7}$, with an amplitude that yields an average comoving density of $\sim 8 \times 10^{-6} h^3 Mpc^{-3}$. Both simulations yield results that are consistent with the redshift distribution of the observed flux-limited sample of clusters. Furthermore, we find that plausible variations in relation (4) do not produce significant changes in the results.

The *mean* richness of the X-ray clusters as a function of redshift is presented in Figure (2). In the flux-limited simulations, there is a strong increase of richness with redshift. By constrast, the mean richness in volume-limited samples is constant. Approximately 30% of the clusters are poor ($R \leq 0$), consistent with the observed sample of Romer *et al.* (1993).

The correlation function of the simulated flux-limited sample is presented in Figure 3. It is compared with the X-ray cluster observations of Romer et al. (1993). The agreement between the observations and simulations is excellent. The simulations yield $r_o \approx 14 h^{-1}$Mpc for the flux-limited sample, consistent with the observed $r_o = 13.7 \pm 2.3 h^{-1}$Mpc. The correlation function of the simulated volume-limited rich $R \geq 1$ clusters (with $n = 6 \times 10^{-6} h^3 \mathrm{Mpc}^{-3}$, $d = 55 h^{-1}$Mpc) is also shown, for comparison; this function matches well the observed $R \geq 1$ correlations, with $r_o \approx 21 h^{-1}$Mpc (Bahcall & Soneira 1983; Postman et al. 1992; Peacock & West 1992).

Figure 3 shows that the flux-limited sample exhibits a lower correlation amplitude than the volume-limited, richness-limited sample of comparable average number density. This is expected due to the "richness-mixed" nature of the flux-limited sample. In the present case, the correlation scales of the flux-limited and

the richness-limited samples satisfy

$$r_o(\text{X}-\text{ray flux}-\text{limited}) \approx \frac{2}{3} r_o(R \geq 1) \quad , \tag{5}$$

with $r_o(R \geq 1) \approx 21h^{-1}$Mpc and r_o(X$-$ray flux$-$limited) $\approx 14h^{-1}$Mpc, as observed. The results are insensitive to reasonable variations in the $L_x(M_{\text{cluster}})$ relation. As an example, we present in Fig. 3 the correlation function for the case $L_x(0.1-2.4) = 3.5 \times 10^{42}(M/10^{14}M\odot)^{1.7}$ergs s^{-1}, which also matches the observed cluster density distribution (Fig. 1).

3. CONCLUSIONS

We show that the spatial correlation function of a flux-limited sample of X-ray selected clusters of galaxies exhibits a correlation scale that is smaller than the correlation scale of a volume-limited, richness-limited sample of comparable average number density (Fig. 3). This is expected due to the "richness-mix" nature of the flux-limited sample, which contains poor clusters nearby and rich clusters farther away.

We show that the correlation scale of the new flux-limited X-ray cluster sample from ROSAT (Romer *et al.* 1993) is expected to be r_o(X$-$ray flux$-$limited) $\approx$ $\frac{2}{3} r_o(R \geq 1) \approx 14h^{-1}$ Mpc, as observed. We conclude that the new observations of X-ray clusters from ROSAT exhibit a correlation function that is consistent with, and is actually predicted from, the richness-dependent cluster correlation and $r_o(R \geq 1) \approx 21h^{-1}$Mpc.

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FIGURE CAPTIONS

Fig. 1– Redshift distribution of the flux-limited X-ray clusters. The X-ray cluster observations of Romer *et al.* (1993) are shown by the faint histogram. Two simulated samples (§2) are represented by the dark and dashed histograms. $dN(z)$ represents the relative number of clusters (i.e., fraction of total) in each redshift bin. (A volume-limited sample yields $dN(z) \propto z^2$).

Fig. 2– The *mean* richness class of the flux-limited X-ray cluster samples as a function of redshift. The two simulated samples (Fig. 1, §2) are shown. Also presented, for comparison, are the horizontal lines for the volume-limited, richness-limited $R \geq 1$ and $R \geq 0$ clusters.

Fig. 3– Cluster correlation function: the expected difference between the cluster correlation function of a volume-limited $R \geq 1$ cluster sample (faint line, with $r_o \approx 21h^{-1}$Mpc), and the relevant flux-limited X-ray cluster correlations ($F_x \geq 10^{-12}$ergs cm^{-2} sec^{-1}; dark and dashed lines, $r_o \approx 14h^{-1}$Mpc). The flux-limited sample is expected to exhibit weaker correlations than the $R \geq 1$ complete sample. The observed flux-limited X-ray cluster correlations (Romer *et al.* 1993), shown by the solid dots, are consistent with the expected flux-limited correlation function and $r_o(R \geq 1) \approx 21h^{-1}$Mpc.

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